

This is a repository copy of *A Preindustrial Sea-Level Rise Hotspot Along the Atlantic Coast of North America*.

White Rose Research Online URL for this paper:  
<https://eprints.whiterose.ac.uk/157868/>

Version: Published Version

---

**Article:**

Gehrels, Willem Roland, Dangendorf, S., Barlow, N. et al. (5 more authors) (2020) A Preindustrial Sea-Level Rise Hotspot Along the Atlantic Coast of North America. *Geophysical Research Letters*. e2019GL085814. ISSN 0094-8276

<https://doi.org/10.1029/2019GL085814>

---

**Reuse**

This article is distributed under the terms of the Creative Commons Attribution (CC BY) licence. This licence allows you to distribute, remix, tweak, and build upon the work, even commercially, as long as you credit the authors for the original work. More information and the full terms of the licence here:  
<https://creativecommons.org/licenses/>

**Takedown**

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing [eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk) including the URL of the record and the reason for the withdrawal request.

# Geophysical Research Letters

## RESEARCH LETTER

10.1029/2019GL085814

### Key Points:

- An episode of rapid sea-level rise occurred in the 18th century along the Atlantic coast of North America (Nova Scotia to Cape Hatteras)
- The 18th century and previously identified 20th century hotspots occur in similar geographic regions
- We hypothesize that these centennial sea-level changes are related to variations in Arctic land-ice mass

### Supporting Information:

- Supporting Information S1
- Table S9
- Table S1
- Table S2
- Table S3
- Table S4
- Table S5
- Table S6
- Table S7
- Table S8
- Table S10
- Table S11
- Table S12

### Correspondence to:

W. R. Gehrels,  
roland.gehrels@york.ac.uk

### Citation:

Gehrels, W. R., Dangendorf, S., Barlow, N. L. M., Saher, M. H., Long, A. J., Woodworth, P. L., et al. (2020). A preindustrial sea-level rise hotspot along the Atlantic coast of North America. *Geophysical Research Letters*, 47, e2019GL085814. <https://doi.org/10.1029/2019GL085814>

Received 19 OCT 2019

Accepted 11 FEB 2020

Accepted article online 13 FEB 2020

© 2020. The Authors.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

## A Preindustrial Sea-Level Rise Hotspot Along the Atlantic Coast of North America

W. R. Gehrels<sup>1</sup>, S. Dangendorf<sup>2,3</sup>, N. L. M. Barlow<sup>4</sup>, M. H. Saher<sup>5</sup>, A. J. Long<sup>6</sup>, P. L. Woodworth<sup>7</sup>, C. G. Piecuch<sup>8</sup>, and K. Berk<sup>9</sup>

<sup>1</sup>Department of Environment and Geography, University of York, York, UK, <sup>2</sup>Center for Coastal Physical Oceanography, Department of Ocean, Earth and Atmospheric Sciences, Old Dominion University, Norfolk, VA, USA, <sup>3</sup>Research Institute for Water and Environment, University of Siegen, Siegen, Germany, <sup>4</sup>School of Earth and Environment, University of Leeds, Leeds, UK, <sup>5</sup>School of Ocean Sciences, Bangor University, Anglesey, UK, <sup>6</sup>Department of Geography, Durham University, Durham, UK, <sup>7</sup>National Oceanography Centre, Liverpool, UK, <sup>8</sup>Physical Oceanography Department, Woods Hole Oceanographic Institution, Woods Hole, MA, USA, <sup>9</sup>Department of Mathematics, University of Siegen, Siegen, Germany

**Abstract** The Atlantic coast of North America north of Cape Hatteras has been proposed as a “hotspot” of late 20th century sea-level rise. Here we test, using salt-marsh proxy sea-level records, if this coast experienced enhanced sea-level rise over earlier multidecadal-centennial periods. While we find in agreement with previous studies that 20th century rates of sea-level change were higher compared to rates during preceding centuries, rates of 18th century sea-level rise were only slightly lower, suggesting that the “hotspot” is a reoccurring feature for at least three centuries. Proxy sea-level records from North America (Iceland) are negatively (positively) correlated with centennial changes in the North Atlantic Oscillation. They are consistent with sea-level “fingerprints” of Arctic ice melt, and we therefore hypothesize that sea-level fluctuations are related to changes in Arctic land-ice mass. Predictions of future sea-level rise should take into account these long-term fluctuating rates of natural sea-level change.

**Plain Language Summary** Measurements of sea-level change have shown that during the 20th century sea-level rise along the Atlantic coast of North America between Cape Hatteras and Nova Scotia has been faster than the global average. We investigated whether this anomaly also occurred earlier by reconstructing historical sea-level changes from salt-marsh sediments and microscopic salt-marsh fossils (foraminifera). We found evidence in three locations (Nova Scotia, Maine, and Connecticut) for rapid sea-level rise in the 18th century, which was almost as rapid as the 20th century sea-level rise. Using additional sea-level reconstructions from across the North Atlantic, we propose an explanation for the periods of enhanced sea-level rise. We hypothesize that they occur during distinct phases of the North Atlantic Oscillation and during periods of enhanced ice melt in the Arctic. The fluctuations are a reoccurring feature and should be considered in planning for future sea-level rise and coastal hazards.

## 1. Introduction

Recent studies have reported that since the 1950s rates of sea-level rise have been anomalously high along the Atlantic coast of North America north of Cape Hatteras—a region that has since come to be known as a sea-level rise “hotspot” (Boon, 2012; Kenigson & Han, 2014; Sallenger et al., 2012). The high rates in this “hotspot” could present significant coastal risks for large population centers if they are a persistent and reoccurring feature. The likely future sea-level rise in New York City has already been shown to be up to 32% greater than the global mean by the end of the 21st century due to the combined effects of glacial isostatic adjustment (GIA), Antarctic mass loss, and weakening of the Atlantic Meridional Overturning Circulation (AMOC) (Kopp et al., 2014). Therefore, any compounding process that generates additional “hotspots” of sea-level rise in this region would exacerbate the problem and must also be taken into account in future sea-level projections.

It has been suggested that the recently observed sea-level acceleration along the Atlantic coast of North America was caused by steric changes and mass redistributions associated with a possible weakening of the AMOC (Sallenger et al., 2012). Others have argued that changes in wind stress along the Scotian Shelf and in the Gulf of Maine, as well as local atmospheric pressure fluctuations, are important driving

mechanisms that contribute to sea-level variability in this region over interannual to multidecadal time-scales (Andres et al., 2013; Piecuch, Calafat, et al., 2019; Thompson et al., 2016; Woodworth et al., 2014, 2017). Correlations with the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO) indices have also been observed (Kenigson & Han, 2014; Kopp, 2013) as well as associations with changes in the latitude and strength of the Gulf Stream (Ezer et al., 2013; Kopp, 2013; Levermann et al., 2005; Yin & Goddard, 2013).

Studies of this region's "hotspot" have thus far only used instrumental sea-level observations and models over relatively short intervals of time (<100 yr), and they are concerned with the recent era when global climate and sea level were, at least partially, controlled by anthropogenic forcing (Slangen et al., 2016). Moreover, the location of "hotspots" varies between studies. For example, in some early modelling papers (Landerer et al., 2007; Yin et al., 2009), the "hotspot" appeared as a broad region of enhanced sea-level rise from Cape Hatteras, through the Mid Atlantic Bight (MAB) and Gulf of Maine, to Atlantic Canada, with perhaps the strongest signal off Newfoundland. In contrast, the pattern of accelerated sea-level rise that Sallenger et al. (2012) found using tide gauges was restricted to the MAB and southern New England; it showed either no acceleration or significant deceleration over the Gulf of Maine and Atlantic Canada—regions that the models (Landerer et al., 2007; Yin et al., 2009) suggested should also be experiencing accelerating sea-level rise.

In this paper, we use longer, high-resolution proxy records to investigate (i) whether "hotspots" of sea-level rise have occurred along the Atlantic coast of North America in the preindustrial past, (ii) whether these "hotspots" have occurred at particular locations or along the entire coastline, and (iii) whether they are consistent with those found in tide-gauge records and modelling studies. Our proxy records are reconstructed from microfossils preserved in salt-marsh sediments (see Supporting Information S1). Salt marshes are capable of recording decimeter-scale historical sea-level variations over past centuries with high precision and accuracy (Gehrels, 2000). All previously published North American Atlantic sea-level records based on salt-marsh sediments demonstrate that sea-level rise in the 20th century was faster than in any previous century, but multidecadal episodes of enhanced regional sea-level rise from before the 20th century have not been reported (Kopp et al., 2016).

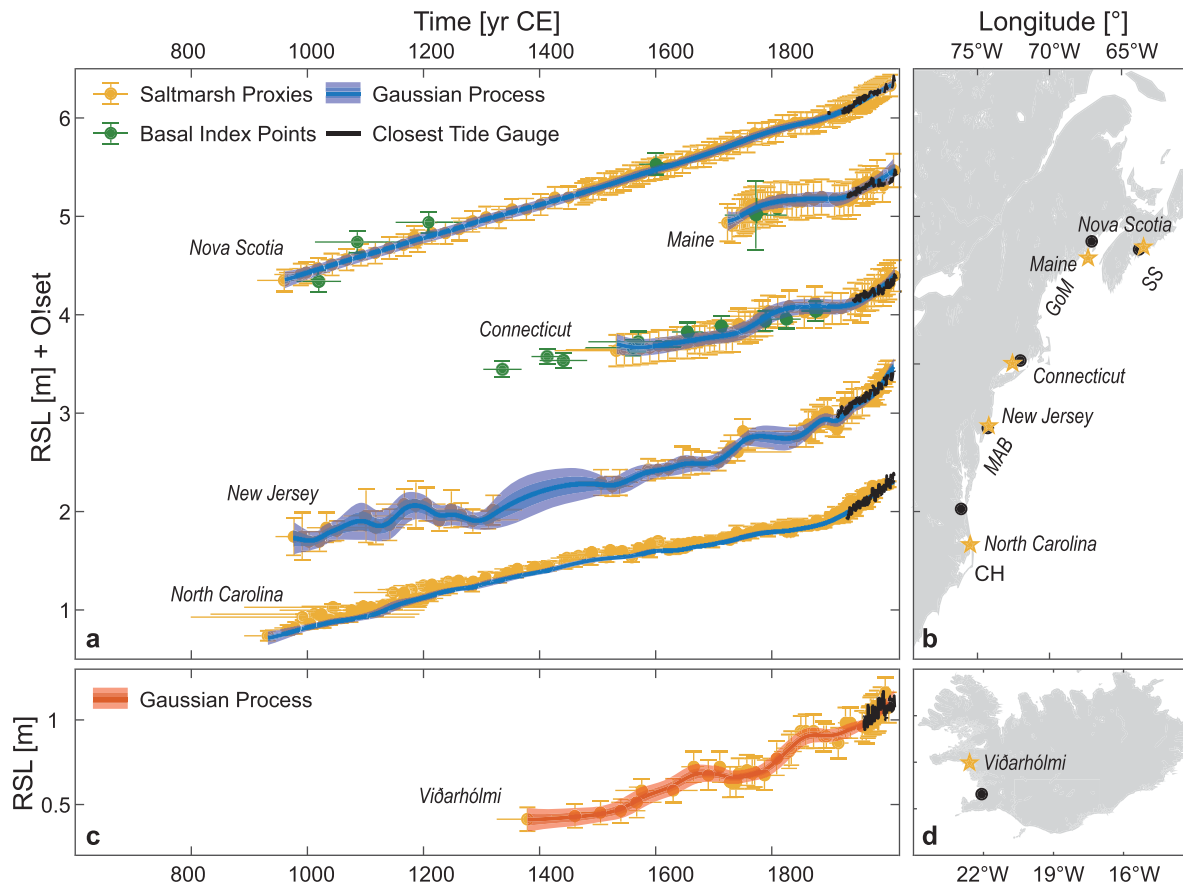
## 2. Materials and Methods

We present three new high-resolution proxy records of multidecadal- to centennial-scale sea-level variability (typically one data point per 5–10 yr and  $\pm 0.1$ – $0.3$  m vertical precision at 2 sigma) reconstructed from salt marshes in Nova Scotia, Maine, and Connecticut (Figure 1a). Lower resolution sea-level reconstructions have previously been published for these locations (Donnelly et al., 2004; Gehrels et al., 2002, 2005), but we refine and enhance these records by adding more than 30 new radiocarbon analyses,  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  measurements as well as other biological and geochemical age markers, together with new microfossil core analyses in an attempt to detect periods of enhanced sea-level rise not previously reported in proxy studies of late Holocene sea-level change along the Atlantic coast of North America.

Our interest is in identifying multidecadal to centennial changes in the rates of sea-level change. Therefore, we follow Cahill et al. (2015) and apply a Gaussian process regression approach (Rasmussen & Williams, 2006) that models relative sea level at each site by taking the corresponding vertical and chronological uncertainties into account and provides probabilistic estimates of past rate changes. The Gaussian process priors are described by a superposition of a linear trend and temporal fluctuations in which the temporal covariance is represented as a Matérn function with a smoothness factor of  $3/2$  and a characteristic time scale of centuries. The prior amplitude of the sea-level variability has been chosen individually at each site. Vertical and chronological errors are both assumed to be normally distributed. Solutions are generated numerically using a Monte Carlo approach with 1,000 simulations per site. The 1,000-member simulation is used to determine statistics of the preindustrial sea-level variability.

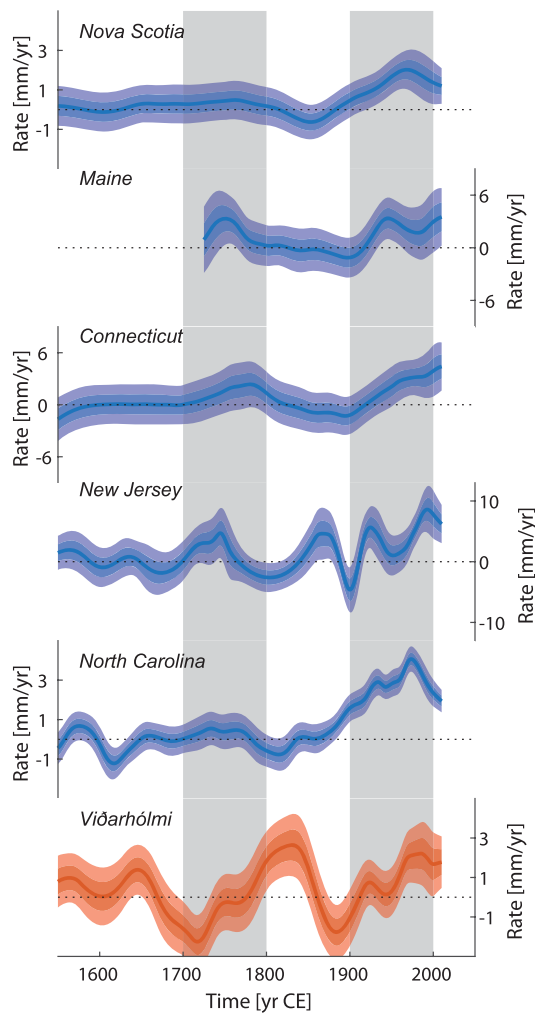
## 3. Historical Sea-Level Changes

The resulting three sea-level reconstructions, plus previously published records from New Jersey (Kemp et al., 2013) and North Carolina (Kemp et al., 2011), are shown in Figure 1. To place the records in a larger-scale geographical context, a recent record from Viðarhólmi, Iceland, is also shown (Gehrels et al., 2006; Saher et al., 2015). The record from Nova Scotia (Chezzetcook) spans a full millennium and is arguably



**Figure 1.** Relative sea-level reconstructions for Chezzetcook (Nova Scotia), Sanborn Cove (Maine), Barn Island (Connecticut), all from this study, New Jersey (Kemp et al., 2013), North Carolina (Kemp et al., 2011), and Viðarhólmi (Iceland) (Gehrels et al., 2006; Saher et al., 2015) and tide-gauge records (Holgate et al., 2013). (a,c) Temporal sea-level evolution since 900 CE for the four proxy records. Yellow crosses are proxy sea-level estimates from cores with 2 sigma vertical and age uncertainties. The red crosses are basal sea-level index points (Gehrels, 1999), immune to compaction, and show that records are not significantly affected by compaction. Also shown are tide-gauge records from nearby stations (black lines, enlargements can be found in the Supporting Information S1) and a Gaussian Process fitted to the individual index points (blue) with 1 and 2 sigma uncertainties from 1,000 Monte Carlo simulations as shading. (b,d) Map with locations of proxy (yellow stars) and tide-gauge records (black dots). Sea-level index points are tabulated in Tables S4–S6. SS—Scotian Shelf, GoM—Gulf of Maine, MAB—Mid Atlantic Bight, CH—Cape Hatteras.

the best-dated sea-level reconstruction over this time interval from any coastline in the world (70 dated levels, Table S1). The Maine and Connecticut sea-level records span the last ~300 and ~450 yr, respectively, and help to constrain the spatial and temporal extent of recent sea-level signals observed in Nova Scotia. The most recent part of each record is compared to nearby tide-gauge observations obtained from the Permanent Service for Mean Sea Level (PSMSL) (Holgate et al., 2013) (Figures 1a and S7). In all cases, 20th century sea-level trends from our proxy reconstructions agree with those from nearby tide-gauge records in the common periods of overlap (Figure S8) demonstrating that the reconstructions accurately capture recent multidecadal-to-centennial sea-level changes along these coastlines. We also compared the sea-level reconstructions to sea-level index points obtained from the base of the Holocene lithostratigraphic sections (Donnelly et al., 2004; Gehrels, 1999; Gehrels et al., 2005) to assess possible compaction in the sequences. If there were significant compaction in our records, we would expect the points from the basal sections, which are all located directly on a hard substrate, to plot higher than the reconstructions. However, they are in good agreement (Figure 1a), so we conclude that compaction has little impact on our sea-level records. Partly due to spatially variable crustal motion rates controlled by GIA, the long-term sea-level trends differ between the sites (Piecuch et al., 2018). We adjusted the sea-level records for GIA by removing the linear late Holocene trend for the common period between 4000 cal yr BP and 1900 CE (Engelhart & Horton, 2012), which in Nova Scotia is 1.7 mm/yr (Gehrels et al., 2005), in Maine is 0.7 mm/yr (Gehrels, 1999; Gehrels



**Figure 2.** Sea-level changes from proxy records along the North American Atlantic (blue) and Icelandic (red) coast. Shown are the nonlinear trends calculated by a Gaussian Process Regression including their 1 and 2 sigma uncertainties (dark and light blue/red bands, respectively) for the six salt-marsh reconstructions corrected for site-specific GIA effects. The black dotted line marks a rate of 0 mm/yr in each panel.

et al., 2002), and in Connecticut is 1.0 mm/yr (Donnelly et al., 2004). For the North Carolina sea-level reconstruction, which is based on two nearby sites in Sand Point and Tump Point, we used GIA corrections of 1.0 and 0.9 mm/yr, respectively (Kemp et al., 2011). The New Jersey and Viðarhólmi records were corrected for a GIA contribution of 1.4 and 1 mm/yr, respectively (Gehrels et al., 2006; Kemp et al., 2013).

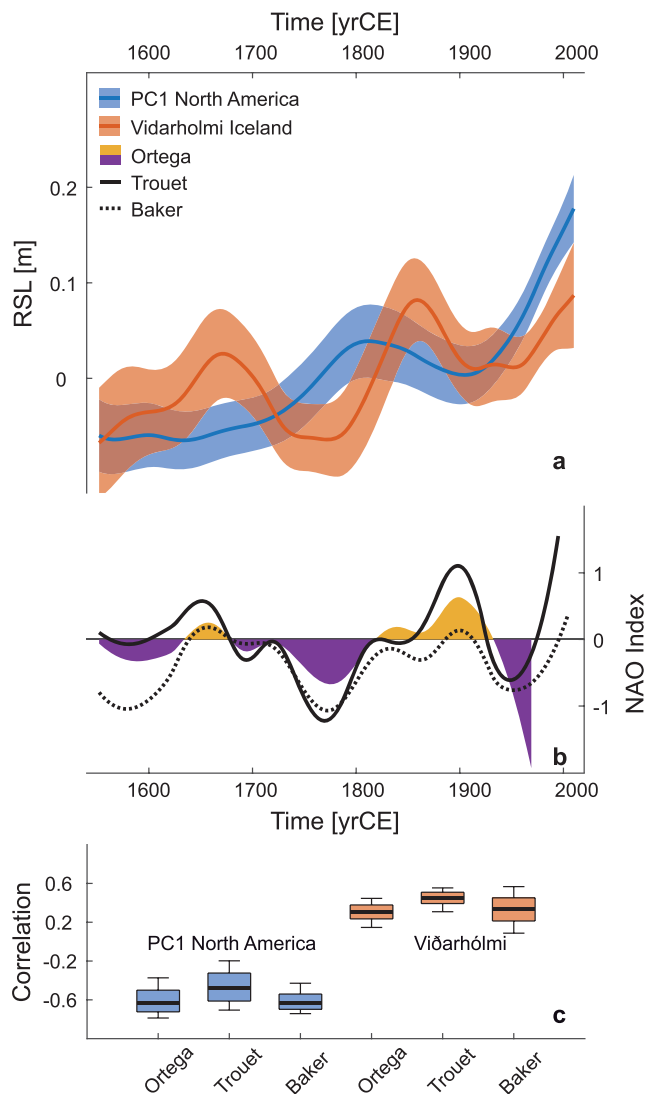
The rates of the GIA-corrected sea-level (GCSL) reconstructions from all sites are shown in Figure 2 and are marked by two distinct features. The first feature is the 19th to 20th century GCSL acceleration, which is visible in all five North American records as well as the record from Iceland, although their exact timing and amplitude may differ between sites. This feature is also present in other salt-marsh-based sea-level reconstructions from the Atlantic coast of North America (Kopp et al., 2016). The second feature is a previously unreported, multidecadal-centennial GCSL fluctuation along the North American Atlantic coast, with maximum rates of rise occurring in the middle-to-late 18th century, and lower or negative rates thereafter. The timing appears to differ slightly from record to record, most likely due to dating uncertainties. Based on the 1,000 Monte Carlo ensemble members at each site, we determine for five sites best estimates for the timing of maximum rates of change, over the period 1550 to 1850, as follows: 1735 (North Carolina), 1745 (New Jersey), 1752 (Maine), 1762 (Nova Scotia), and 1783 (Connecticut). Moreover, between 85% (Nova Scotia) and 98% (New Jersey) of ensemble members show greater-than-zero rates averaged over the 18th century. These numbers suggest significant, larger-than-usual (with respect to longer-term GIA) rates of change peaking in the middle-to-late 18th century. The GCSL fluctuation is more pronounced in Maine and Connecticut, compared to Nova Scotia and North Carolina. In Connecticut, GCSL rates were close to zero before ~1700 and increased to values of  $\sim 2.4 \pm 2.4$  mm/yr ( $\pm$  indicates twice the standard error) towards the end of the 18th century. High preindustrial GCSL rates are similarly visible in the Maine record ( $\sim 3.2 \pm 3.2$  mm/yr), although the record only starts in the mid-18th century. The New Jersey record includes the late 18th century period of enhanced sea-level rise but overall shows greater variability than all other records. In Nova Scotia and North Carolina, rates during this period were also enhanced compared to long-term background rates of change, but they did not exceed values of  $\sim 0.5 \pm 1.0$  mm/yr. It is important to note that spatial variations in the ampli-

tudes of multidecadal sea-level variations along this coastline are also observed in tide-gauge records over the 20th century (Sallenger et al., 2012). Interestingly, relatively high preindustrial GCSL rates are also seen in the Viðarhólmi data from Iceland. The records from North America and Iceland are out of phase: rates of change in Iceland are anomalously low around 1700 CE and high around 1800 CE, suggesting that peak rates of preindustrial GCSL rise occurred in North America ~60–80 yr earlier than in Iceland. Possible reasons for this are considered below.

While the high 18th century rates of sea-level rise are a consistent feature in our records across sites, patterns become more complex in earlier periods. For example, the New Jersey and North Carolina records are very similar, but in North Carolina sea-level variability was more muted prior to the 18th century (a finding that is robust against different choices of the Gaussian process priors). These differences between records might be explained by different driving mechanisms or could reflect issues with the salt-marsh reconstructions (e.g., dating resolution or quality of transfer functions). These remain open questions.

The multidecadal to centennial sea-level fluctuations found in our records are not seen in previously published reconstructions. There are several possible explanations for this. First, some of the recently published sea-level records from the Atlantic coast of North America (Kemp et al., 2011, 2014) are from south of Cape





**Figure 3.** Link between coastal sea-level changes along the east coast of North America and large-scale climate in the North Atlantic region. (a) First principle component (PC1) of GCSL changes along the Atlantic coast of North America (blue) and GCSL from Viðarhólmi (red). Both time series have been corrected for the simultaneous GMSL from Kopp et al. (2016). (b) Annual NAO index from Ortega et al. (2015) and winter NAO reconstructions from Trouet et al. (2009) and Baker et al. (2015), all centennially smoothed. (c) Correlations between the GCSL from salt-marsh reconstructions and the three different NAO reconstructions. Correlations have been calculated for each of the 1,000 Monte-Carlo realizations of the Gaussian Process regression. The boxplots represent different percentiles (2.5, 16, 50, 84, 97.5) of correlations.

Hatteras and outside of the main hotspot region of the MAB identified by Sallenger et al. (2012) from tide-gauge records over the period 1950–2009. Second, the proxy records that are from that region, i.e. New York City (Kemp et al., 2017) and eastern Connecticut (Kemp et al., 2015), lack high-resolution data in the 18th and 19th centuries; we suggest that more detailed investigations here could reveal the same sea-level fluctuations.

#### 4. Driving Mechanisms

We consider local and regional driving mechanisms to explain the high rates of preindustrial sea-level rise observed in our records. In the Gulf of Maine, tidal range changes have been considered to be important locally over longer (millennial) timescales (Gehrels et al., 1995), but the large increases in M2 tidal amplitudes observed there during the 20th century are not thought to be representative of the longer term (Ray & Talke, 2019). Dynamic coastal barrier and spit systems, which can generate local tidal range changes in back-barrier settings, are absent in our study sites. Instead, we suggest large-scale climate variation as a potential driver of the multidecadal-centennial GCSL variations.

To probe potential climate-related driving mechanisms, we consider the common GCSL signal across the North American Atlantic coast sites, calculating the first principal-component (PC) time series from an empirical orthogonal function (EOF) analysis of GCSL from the three longest salt-marsh reconstructions in Nova Scotia, Connecticut, and North Carolina over their common period, ~1550 to 2010 CE (Figure 3a). To isolate regional behavior, the time series of global mean sea level from Kopp et al. (2016) is removed from the reconstructions prior to performing the EOF analysis. The first PC accounts for 81% of the variance and is highly representative of the three sites. Consistent with the individual reconstructions (Figure 2), the first PC is characterized by low GCSL rates in the 17th century, a period of rapid rise during the 18th century, and a fall over the 19th century. Since the turn of the 20th century, GCSL rates have increased to unprecedented and larger-than-global-average values (Figure 3a). The Viðarhólmi salt-marsh reconstruction also shows larger-than-global-average rates of GCSL rise over the last century. Prior to that, multidecadal-centennial variations in GCSL at Iceland are out of phase and have ~30% larger amplitudes than those on the North American Atlantic coast (Figure 3a).

The out-of-phase relationship between preindustrial GCSL inferred from salt-marsh records along the Atlantic coast of North America and Iceland could result from mass and density redistribution within the ocean due to exchanges with other components of the climate system on centennial timescales. A major mode of surface climate variation in the North Atlantic is the NAO. To test for a connection between coastal sea level and large-scale surface climate on long timescales, we compare the GCSL reconstructions, adjusted for global-mean sea level (Kopp et al.,

2016), to three recent reconstructions of the NAO (Baker et al., 2015; Ortega et al., 2015; Trouet et al., 2009) (Figure 3b). Depending on choice of NAO reconstruction, we compute best estimates of the correlation coefficient between the first PC of North American Atlantic coast GCSL and the NAO of between  $-0.48$  and  $-0.63$ , whereas best-estimate correlation coefficients between Iceland GCSL and the NAO fall between  $0.31$  and  $0.45$  (Figure 3c). In all cases, correlations are statistically significant at the  $p < 0.01$  level, suggesting that processes related to the NAO play an important role in generating the centennial GCSL fluctuations seen in the salt-marsh reconstructions.

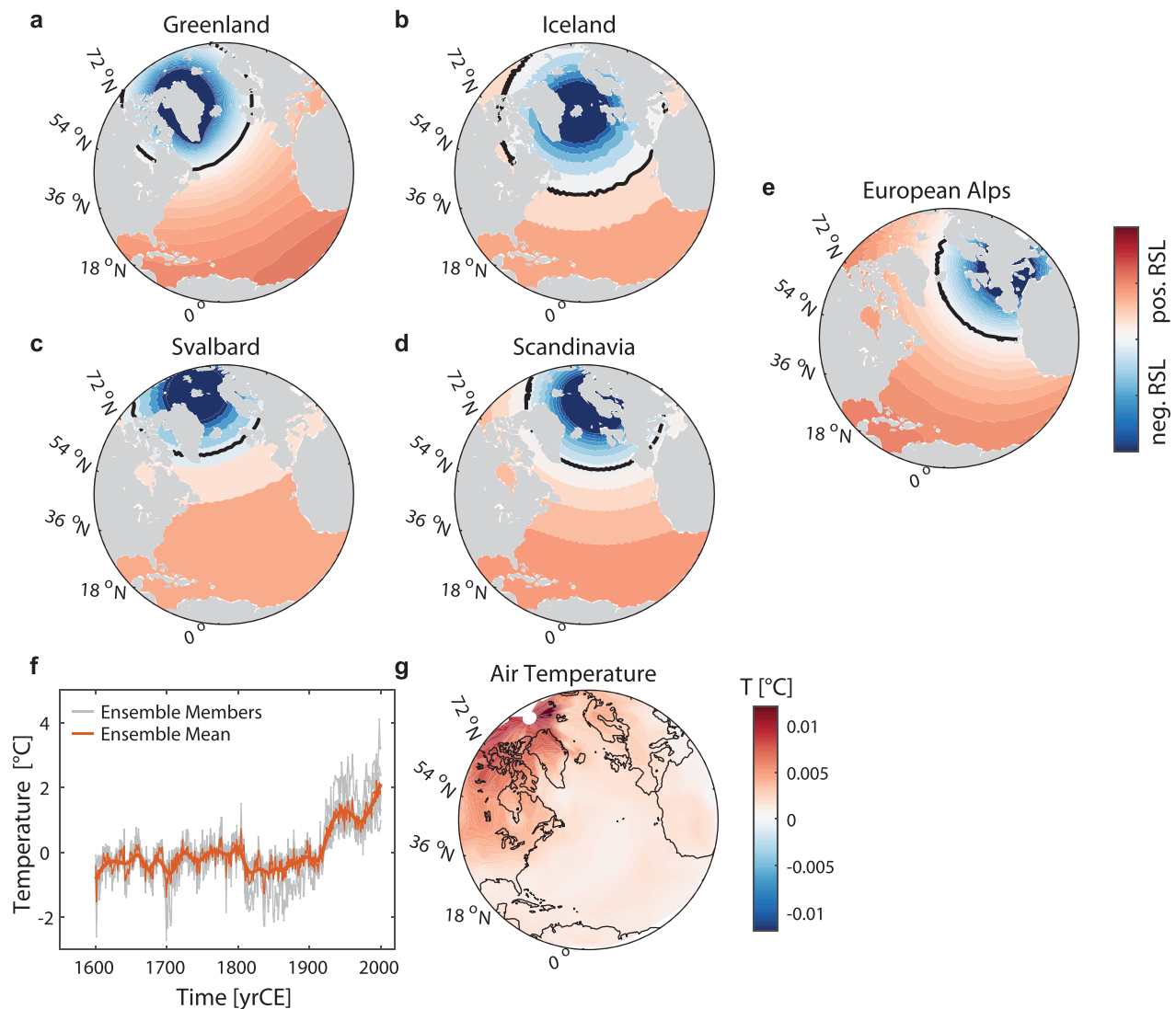
Similar relationships between coastal sea level and large-scale surface climate are seen in instrumental data records covering shorter, more recent periods (Tsimplis et al., 2006; Woolf et al., 2003; Yan et al., 2004). The first PC from an EOF analysis of monthly tide-gauge sea-level data at Halifax, Eastport, and New London (locations near our three salt marshes in Nova Scotia, Maine, and Connecticut, respectively) explains 91% of the variance in these records (Figure S9). The first PC of sea level from these three tide gauges is significantly anti-correlated (coefficient  $\sim -0.31$ ,  $p < 0.01$ ) with monthly values of the NAO, whereas sea level observed at the Reykjavik tide gauge (near Viðarhólmi) is significantly correlated with the NAO (coefficient  $\sim 0.51$ ,  $p < 0.01$ ). These results show, over timescales ranging from months to centuries, that sea levels in Nova Scotia, Maine, and Connecticut vary in concert with one another and that sea levels along the North American Atlantic coast and in Iceland are significantly related to the NAO but with opposite sign.

It remains to identify what processes mediate the relationship between sea level along the Atlantic coast of North America and Iceland, as seen in the salt-marsh records, and their links to changes in ocean circulation and large-scale climate on centennial timescales. One possibility is that NAO-related ocean dynamics, driven locally or remotely by the atmosphere, plays a role (Curry & McCartney, 2001; Marshall et al., 2001). Local wind and pressure forcing can drive coastal sea level fluctuations of  $\sim \pm 5$ –10 cm on timescales of months to years (e.g., Andres et al., 2013; Woodworth et al., 2014; Piecuch, Calafat, et al., 2019). These forcing factors have predominantly white spectra, as does the attendant ocean response in shallow, weakly stratified regions near the coast (e.g., Frankignoul et al., 1997; Piecuch, Dangendorf, et al., 2019; Willebrand et al., 1980). Any sea-level fluctuations related to these processes would thus have magnitudes  $< 1$  cm on the centennial periods of interest. Therefore, we reason that such local atmospheric forcing mechanisms alone are unlikely to explain the larger-magnitude centennial behavior observed in the proxy records.

To consider the influence of larger-scale atmosphere-ocean dynamics, including connections to possible changes in the AMOC, we examine annual sea-level fields from five coupled climate models participating in the CMIP5/PMIP3 last-millennium experiment spanning 850–1850 CE (Schmidt et al., 2012). We compare modelled sea level from Nova Scotia, Maine, and Connecticut to sea level near Iceland, as well as to the NAO. Time series are smoothed with a 100-yr Hamming window. Sea-level variations over these timescales from the climate models are on the order of  $\sim \pm 1$ –2 cm (Figure S10), which is much smaller than the  $\sim \pm 5$ –10-cm fluctuations apparent in the salt-marsh records (Figure 3). Correlations between North America and Iceland sea levels are either statistically insignificant or significantly positive in the models (Figure S10), which is distinct from the significant negative correlation observed in the proxies (Figure 3), but consistent with other idealized climate-model simulations designed to quantify the ocean's centennial response to surface-heat-flux forcing associated with the NAO (Delworth & Zeng, 2016). These results suggest that large-scale atmosphere-ocean dynamics is not of leading importance in generating the sea-level changes seen in the salt-marsh records, that there are errors in contemporary climate models that consistently preclude realistic simulations of sea level on centennial timescales, or both.

Proxy reconstructions of AMOC changes, interpreted in light of basic ocean dynamics principles, give further evidence, arguing against an explanation of the coastal sea-level changes primarily in terms of large-scale ocean circulation. Thermal wind balance, applied to a flat-bottomed ocean with vertical side-walls, suggests that a  $\sim 5$ –10-cm increase in sea level on the Atlantic coast of North America, such as observed during the 18th century in the salt-marsh records, should be accompanied by a contemporaneous  $\sim 5$ -Sv decline in the AMOC (e.g., Little et al., 2019). Yet, some reconstructions of the AMOC based on surface and subsurface ocean temperatures suggest that the AMOC was stable during the 1700s, undergoing decadal fluctuations of no more than  $\sim \pm 1$  Sv (Caesar et al., 2018; Rahmstorf et al., 2015; Thornalley et al., 2018). However, other records suggest considerable variability during this time and uncertainties of AMOC reconstructions are potentially quite large (Moffa-Sánchez et al., 2019). Overall, there is no obvious relationship between the density of intermediate waters in the Labrador Sea, which declined continuously from  $\sim 1700$  to  $\sim 1900$  CE (Thornalley et al., 2018), and sea level on the Atlantic coast of North America, which increased during the 1700s but decreased during the 1800s relative to the global mean and long-term GIA rates (Figure 3).

Another means for causing the sea-level changes in the salt-marsh records might be through the static response to melting of land-based ice. When ice on land melts, water mass is redistributed at the surface, perturbing Earth's crust, gravity field, and rotation vector, and resulting in spatially variable patterns of sea-level



**Figure 4.** Examples of glacier and ice-sheet gravitational-rotational-deformational effects (“fingerprints”) that have the potential to force an out-of-phase relationship in relative sea level along North American and Icelandic coastline. Shown are (a) Greenland, (b) Iceland, (c) Svalbard, (d) Scandinavia, and (e) European Alps. Also shown are Arctic temperature change extracted from PAGES2k ensemble reconstructions (Neukom et al., 2019) in the form of time series in (f) and as ensemble mean linear trends over 1700–1800 CE period in (g). The thick line in (f) corresponds to a centennially smoothed version of the ensemble mean.

change (Mitrovica et al., 2001). These “fingerprints” are characterized by sea-level fall in the near field of the mass source and greater-than-global-average sea-level rise in the far field. Iceland is proximal to the Greenland Ice Sheet and numerous prominent high-northern-latitude glacier complexes (Greenland, Iceland, Svalbard, Russia, Scandinavia, etc.), the melting of which would lead to opposing sea-level changes along Iceland and eastern North America, with sea-level changes in Iceland larger in amplitude than those along the Atlantic coast of North America (Figure 4).

We use reconstructions of surface temperature history from the PAGES2k project (Neukom et al., 2019) to consider whether enhanced warming and ice melt in the Arctic could have occurred in the 18th century. Compared to the 17th and 19th centuries, the 18th century was a period of relative warmth and warming north of 60°N (Figure 4f). A spatial analysis (Figure 4g) reveals that the warming in the Arctic during this time was more pronounced than in other areas globally. This warming could have caused melting of Arctic land-based ice—the gravitational, rotational, and deformational effects of which would have caused sea-level fall around Iceland in the near field and sea-level rise along the farther-field Atlantic coast of North America. Long glacier length records are rare (Leclercq et al., 2014), but they show some mass loss during the 18th century, especially in the European Alps, Scandinavia, and possibly Iceland (Figure S11). In the



Canadian high Arctic, 18th century warming may have contributed to thinning of the Greenland Ice Sheet (Halfar et al., 2013; Lecavalier et al., 2017) and the retreat of some tide water glaciers (Lea et al., 2014; Motyka et al., 2017). Mass loss along Greenland's periphery is consistent with relative sea-level changes reconstructed from salt marshes in western Greenland (Long et al., 2012) and sea-ice proxy records from the East Greenland Shelf (Kolling et al., 2017). Evidence from six ice cores indicates a warming of Greenland of  $\sim 1.6^{\circ}\text{C}$  between 1710 and 1790, the fastest centennial rate of warming before the 20th century during, at least, the last two millennia (Vinther et al., 2009).

Melting of Arctic land-based ice has been linked to the NAO. For example, Greenland's contributions to global sea-level rise during the Arctic warm period of the 1920s and 1930s have been correlated with a negative phase of the NAO (Chylek et al., 2004; Gregory et al., 2013). Glacier mass loss in Norway and Svalbard during the second half of the 18th century has been attributed to reductions in precipitation due to NAO shifts (Nesje et al., 2008; Røthe et al., 2015). Combined ice core and modelling studies show that snow accumulation rates in Greenland during the past 400 yr were strongly correlated with the NAO but were stable during the 18th century (Box et al., 2013), suggesting that Greenland ice-mass change was linked to temperature, rather than precipitation changes, in the 18th century.

Therefore, multiple lines of evidence (e.g., from climate models, sea-level fingerprints, paleo-climate reconstructions of surface temperature and ocean circulation, glacial and salt-marsh records) support the hypothesis that reduction in Arctic land ice mass, possibly connected to the NAO, was a leading order process contributing to the out-of-phase preindustrial sea-level changes along the coasts of eastern North America and Iceland apparent in salt-marsh records. Future studies that may test this hypothesis require quantification of historical ice melt, and assessment of resulting sea-level fingerprints in additional locations using well-dated, high-resolution proxy sea-level records.

## 5. Conclusions

We provide evidence, based on proxy sea-level reconstructions derived from salt-marsh sediments from the Atlantic coast of North America, for a preindustrial sea-level rise “hotspot” during the 18th century. The rate of sea-level rise during this period was only slightly smaller than during the latter half of the 20th-century. Indeed, the region where the most pronounced sea-level rise during this preindustrial period is recorded (Nova Scotia to Cape Hatteras) is similar to the area where, during the last half century or so, tide-gauge observations suggest a recent “hotspot” of accelerated sea level rise. We propose that the magnitude ( $\sim \pm 5\text{--}10\text{ cm}$ ) and duration ( $\sim 50\text{--}100\text{ yr}$ ) of this preindustrial sea-level rise event along eastern North America, along with its out-of-phase relationship to sea-level fluctuations in Iceland and coincidence with centennial variations in the NAO, favor an explanation in terms of mass changes of Arctic land ice, although we acknowledge that uncertainties are large and other processes (e.g., involving an ocean contribution) cannot be entirely excluded. Examination of sea-level output from coupled climate-model experiments, geometries (“fingerprints”) of sea-level change resulting from land-ice melt, and paleoclimate proxy records of Arctic temperature all support the hypothesis that centennial variations in the retreat and advance of Arctic glaciers render important contributions to the sea-level long-term variability seen in the salt-marsh records. Our findings suggest that enhanced rates of sea-level rise along eastern North America are not necessarily symptomatic of anthropogenic forcing, as was argued in past work (Sallenger et al., 2012), but might arise from other forcing mechanisms in the coupled climate system. Our results also suggest that these multidecadal-centennial periods of low or high sea level might dampen or amplify any future sea-level signal that is generated by greenhouse-gas forcing, and should be taken into account in projections of future coastal vulnerability and risk.

## Author Contributions

W.R.G., A.J., and P.L.W. designed research; W.R.G., N.L.M.B. and M.H.S. collected field data; all authors performed research; W.R.G., S.D. and C.G.P. wrote the paper; all authors commented on drafts.

## References

- Andres, M., Gawarkiewicz, G. G., & Toole, J. M. (2013). Interannual sea level variability in the western North Atlantic: Regional forcing and remote response. *Geophysical Research Letters*, 40, 5915–5919. <https://doi.org/10.1002/2013GL058013>

## Acknowledgments

This work is funded by the Natural Environment Research Council (grant NE/G003440/1). All radiocarbon dating was supported by the Natural Environment Research Council Radiocarbon Facility (allocations 1490.0810, 1566.0511, 1604.0112). Mark Wood assisted with fieldwork. Rob Scaife analyzed pollen data for core SN-3.3. Sönke Dangendorf and Kevin Berk acknowledge the University of Siegen for their support within the PEPSEA project. Christopher Piecuch was supported by National Science Foundation awards OCE-1558966 and OCE-1834739. We thank project members Miguel Ángel Morales Maqueda, Chris Hughes, Vassil Roussenov and Ric Williams for valuable discussions. We are grateful to the International Space Science Institute (ISSI; Bern, Switzerland) for support of the International Team “Towards a unified Sea Level Record”. Data used in this paper are freely available online (<https://www.doi.org/10/dgvq>).

- Baker, A., C. Hellstrom, J., Kelly, B. F. J., Mariethoz, G., & Trouet, V. (2015). A composite annual-resolution stalagmite record of North Atlantic climate over the last three millennia. *Scientific Reports*, 5, 10307. <https://doi.org/10.1038/srep10307>
- Boon, J. D. (2012). Evidence of sea level acceleration at U.S. and Canadian tide stations, Atlantic Coast, North America. *Journal of Coastal Research*, 285(2011), 1437–1445. <https://doi.org/10.2112/JCOASTRES-D-12-00102.1>
- Box, J. E., Cressie, N., Bromwich, D. H., Jung, J. H., Van Den Broeke, M., Van Angelen, J. H., et al. (2013). Greenland ice sheet mass balance reconstruction. Part I: Net snow accumulation (1600–2009). *Journal of Climate*, 26(11), 3919–3934. <https://doi.org/10.1175/JCLI-D-12-00373.1>
- Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G., & Saba, V. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature*, 556(7700), 191–196. <https://doi.org/10.1038/s41586-018-0006-5>
- Cahill, N., Kemp, A. C., Horton, B. P., & Parnell, A. C. (2015). Modeling sea-level change using errors-in-variables integrated Gaussian processes. *The Annals of Applied Statistics*, 9(2), 547–571. <https://doi.org/10.1214/15-AOAS824>
- Chylek, P., Box, J. E., & Lesins, G. (2004). Global warming and the Greenland ice sheet. *Climatic Change*, 63(1–2), 201–221. <https://doi.org/10.1023/B:CLIM.0000018509.74228.03>
- Curry, R. G., & McCartney, M. S. (2001). Ocean gyre circulation changes associated with the North Atlantic Oscillation. *Journal of Physical Oceanography*, 31(12), 3374–3400. [https://doi.org/10.1175/1520-0485\(2001\)031<3374:ogccaw>2.0.co;2](https://doi.org/10.1175/1520-0485(2001)031<3374:ogccaw>2.0.co;2)
- Delworth, T. L., & Zeng, F. (2016). The impact of the North Atlantic Oscillation on climate through its influence on the Atlantic meridional overturning circulation. *Journal of Climate*, 29(3), 941–962. <https://doi.org/10.1175/JCLI-D-15-0396.1>
- Donnelly, J. P., Cleary, P., Newby, P., & Ettinger, R. (2004). Coupling instrumental and geological records of sea-level change: Evidence from southern New England of an increase in the rate of sea-level rise in the late 19th century. *Geophysical Research Letters*, 31, L05203. <https://doi.org/10.1029/2003GL018933>
- Engelhart, S. E., & Horton, B. P. (2012). Holocene sea level database for the Atlantic coast of the United States. *Quaternary Science Reviews*, 54, 12–25. <https://doi.org/10.1016/j.quascirev.2011.09.013>
- Ezer, T., Atkinson, L. P., Corlett, W. B., & Blanco, J. L. (2013). Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast. *Journal of Geophysical Research: Oceans*, 118, 685–697. <https://doi.org/10.1002/jgrc.20091>
- Frankignoul, C., Müller, P., & Zorita, E. (1997). A simple model of the decadal response of the ocean to stochastic wind forcing. *Journal of Physical Oceanography*, 27(8), 1533–1546. [https://doi.org/10.1175/1520-0485\(1997\)027<1533:ASMOTD>2.0.CO;2](https://doi.org/10.1175/1520-0485(1997)027<1533:ASMOTD>2.0.CO;2)
- Gehrels, W. R. (1999). Middle and Late Holocene sea-level changes in eastern Maine reconstructed from foraminiferal saltmarsh stratigraphy and AMS 14C dates on basal peat. *Quaternary Research*, 52(3), 350–359. <https://doi.org/10.1006/qres.1999.2076>
- Gehrels, W. R. (2000). Using foraminiferal transfer functions to produce high-resolution sea-level records from salt-marsh deposits, Maine, USA. *The Holocene*, 10(3), 367–376. <https://doi.org/10.1191/095968300670746884>
- Gehrels, W. R., Belknap, D. F., Black, S., & Newnham, R. M. (2002). Rapid sea-level rise in the Gulf of Maine. *The Holocene*, 4, 383–389.
- Gehrels, W. R., Belknap, D. F., Pearce, B. R., & Gong, B. (1995). Modeling the contribution of M2 tidal amplification to the Holocene rise of mean high water in the Gulf of Maine and the Bay of Fundy. *Marine Geology*, 124(1–4), 71–85. [https://doi.org/10.1016/0025-3227\(95\)00033-U](https://doi.org/10.1016/0025-3227(95)00033-U)
- Gehrels, W. R., Kirby, J. R., Prokoph, A., Newnham, R. M., Achterberg, E. P., Evans, H., et al. (2005). Onset of recent rapid sea-level rise in the western Atlantic Ocean. *Quaternary Science Reviews*, 24(18–19), 2083–2100. <https://doi.org/10.1016/j.quascirev.2004.11.016>
- Gehrels, W. R., Marshall, W. A., Gehrels, M. J., Larsen, G., Kirby, J. R., Eiriksson, J., et al. (2006). Rapid sea-level rise in the North Atlantic Ocean since the first half of the nineteenth century. *Holocene*, 16(7), 949–965. <https://doi.org/10.1177/0959683606h1986rp>
- Gregory, J. M., White, N. J., Church, J. A., Bierkens, M. F. P., Box, J. E., Van Den Broeke, M. R., et al. (2013). Twentieth-century global-mean sea level rise: Is the whole greater than the sum of the parts? *Journal of Climate*, 26(13), 4476–4499. <https://doi.org/10.1175/JCLI-D-12-00319.1>
- Halfar, J., Adey, W. H., Kronz, A., Hetzinger, S., Edinger, E., & Fitzhugh, W. W. (2013). Arctic sea-ice decline archived by multicentury annual-Resolution record from crustose coralline algal proxy. *Proceedings of the National Academy of Sciences of the United States of America*, 110(49), 19737–19741. <https://doi.org/10.1073/pnas.1313775110>
- Holgate, S. J., Matthews, A., Woodworth, P. L., Rickards, L. J., Tamisiea, M. E., Bradshaw, E., et al. (2013). New data systems and products at the permanent service for mean sea level. *Journal of Coastal Research*, 29(3), 493–504. <https://doi.org/10.2112/JCOASTRES-D-12-00175.1>
- Kemp, A. C., Bernhardt, C. E., Horton, B. P., Vane, C. H., Kopp, R. E., Peltier, W. R., et al. (2014). Late Holocene sea- and land-level change on the U.S. southeastern Atlantic coast. *Marine Geology*, 357, 90–100. <https://doi.org/10.1016/j.margeo.2014.07.010>
- Kemp, A. C., Hawkes, A. D., Donnelly, J. P., Vane, C. H., Horton, B. P., Hill, T. D., et al. (2015). Relative sea-level change in Connecticut (USA) during the last 2200 yrs. *Earth and Planetary Science Letters*, 428, 217–229. <https://doi.org/10.1016/j.epsl.2015.07.034>
- Kemp, A. C., Hill, T. D., Vane, C. H., Cahill, N., Orton, P. M., Talke, S. A., et al. (2017). Relative sea-level trends in New York City during the past 1500 years. *The Holocene*, 27(8), 1169–1186. <https://doi.org/10.1177/0959683616683263>
- Kemp, A. C., Horton, B. P., Donnelly, J. P., Mann, M. E., Vermeer, M., & Rahmstorf, S. (2011). Climate related sea-level variations over the past two millennia. *Proceedings of the National Academy of Sciences of the United States of America*, 108(27), 11,017–11,022. <https://doi.org/10.1073/pnas.1015619108>
- Kemp, A. C., Horton, B. P., Vane, C. H., Bernhardt, C. E., Corbett, D. R., Engelhart, S. E., et al. (2013). Sea-level change during the last 2500 years in New Jersey, USA. *Quaternary Science Reviews*, 81, 90–104. <https://doi.org/10.1016/j.quascirev.2013.09.024>
- Kenigson, J. S., & Han, W. (2014). Detecting and understanding the accelerated sea level rise along the east coast of the United States during recent decades. *Journal of Geophysical Research: Oceans*, 119, 1365–1382. <https://doi.org/10.1002/2014JC010224>
- Kolling, H. M., Stein, R., Fahl, K., Perner, K., & Moros, M. (2017). Short-term variability in late Holocene sea ice cover on the East Greenland Shelf and its driving mechanisms. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 485, 336–350. <https://doi.org/10.1016/j.palaeo.2017.06.024>
- Kopp, R. E. (2013). Does the mid-Atlantic United States sea level acceleration hot spot reflect ocean dynamic variability? *Geophysical Research Letters*, 40, 3981–3985. <https://doi.org/10.1002/grl.50781>
- Kopp, R. E., Horton, R. M., Little, C. M., Mitrovica, J. X., Oppenheimer, M., Rasmussen, D. J., et al. (2014). Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future*, 2, 383–406. <https://doi.org/10.1002/2014EF000239>
- Kopp, R. E., Kemp, A. C., Bittermann, K., Horton, B. P., Donnelly, J. P., Gehrels, W. R., et al. (2016). Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences*, 113(11), E1434–E1441. <https://doi.org/10.1073/pnas.1517056113>

- Landerer, F. W., Jungclauss, J. H., & Marotzke, J. (2007). Regional dynamic and steric sea level change in response to the IPCC-A1B scenario. *Journal of Physical Oceanography*, 37(2), 296–312. <https://doi.org/10.1175/JPO3013.1>
- Lea, J. M., Mair, D. W. F., Nick, F. M., Rea, B. R., Weidick, A., Kjær, K. H., et al. (2014). Terminus-driven retreat of a major southwest Greenland tidewater glacier during the early 19th century: Insights from glacier reconstructions and numerical modelling. *Journal of Glaciology*, 60(220), 333–344. <https://doi.org/10.3189/2014JofG13J163>
- Lecavalier, B. S., Fisher, D. A., Milne, G. A., Vinther, B. M., Tarasov, L., Huybrechts, P., et al. (2017). High Arctic Holocene temperature record from the Agassiz ice cap and Greenland ice sheet evolution. *Proceedings of the National Academy of Sciences of the United States of America*, 114(23), 5952–5957. <https://doi.org/10.1073/pnas.1616287114>
- Leclercq, P. W., Oerlemans, J., Basagic, H. J., Bushueva, I., Cook, A. J., & Le Bris, R. (2014). A data set of worldwide glacier length fluctuations. *The Cryosphere*, 8(2), 659–672. <https://doi.org/10.5194/tc-8-659-2014>
- Levermann, A., Griesel, A., Hofmann, M., Montoya, M., & Rahmstorf, S. (2005). Dynamic sea level changes following changes in the thermohaline circulation. *Climate Dynamics*, 24(4), 347–354. <https://doi.org/10.1007/s00382-004-0505-y>
- Little, C. M., Hu, A., Hughes, C. W., McCarthy, G. D., Piecuch, C. G., Ponte, R. M., & Thomas, M. D. (2019). The relationship between U.S. east coast sea level and the Atlantic meridional overturning circulation: A review. *Journal of Geophysical Research: Oceans*, 124, 6435–6458. <https://doi.org/10.1029/2019JC015152>
- Long, A. J., Woodroffe, S. A., Milne, G. A., Bryant, C. L., Simpson, M. J. R., & Wake, L. M. (2012). Relative sea-level change in Greenland during the last 700 yrs and ice sheet response to the Little Ice Age. *Earth and Planetary Science Letters*, 315–316, 76–85. <https://doi.org/10.1016/j.epsl.2011.06.027>
- Marshall, J., Johnson, H., & Goodmann, J. (2001). A study of the interaction of the North Atlantic oscillation with ocean circulation. *Journal of Climate*, 14(7), 1399–1421. [https://doi.org/10.1175/1520-0442\(2001\)014<1399:ASOTIO>2.0.CO;2](https://doi.org/10.1175/1520-0442(2001)014<1399:ASOTIO>2.0.CO;2)
- Mitrovica, J. X., Tamisiea, M. E., Davis, J. L., & Milne, G. A. (2001). Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. *Nature*, 409(6823), 1026–1029. <https://doi.org/10.1038/35059054>
- Moffa-Sánchez, P., Moreno-Chamarro, E., Reynolds, D. J., Ortega, P., Cunningham, L., Swingedouw, D., et al. (2019). Variability in the northern North Atlantic and Arctic oceans across the last two millennia: A review. *Paleoceanography and Paleoclimatology*, 34, 1399–1436. <https://doi.org/10.1029/2018PA003508>
- Motyka, R. J., Cassotto, R., Truffer, M., Kjeldsen, K. K., Van As, D., Korsgaard, N. J., et al. (2017). Asynchronous behavior of outlet glaciers feeding Godthåbsfjord (Nuup Kangerlua) and the triggering of Narsap Sermia's retreat in SW Greenland. *Journal of Glaciology*, 63(238), 288–308. <https://doi.org/10.1017/jog.2016.138>
- Nesje, A., Dahl, S. O., Thun, T., & Nordli (2008). The “Little Ice Age” glacial expansion in western Scandinavia: Summer temperature or winter precipitation? *Climate Dynamics*, 30(7–8), 789–801. <https://doi.org/10.1007/s00382-007-0324-z>
- Neukom, R., Steiger, N., Gómez-Navarro, J. J., Wang, J., & Werner, J. P. (2019). No evidence for globally coherent warm and cold periods over the preindustrial Common Era. *Nature*, 571(7766), 550–554. <https://doi.org/10.1038/s41586-019-1401-2>
- Ortega, P., Lehner, F., Swingedouw, D., Masson-Delmotte, V., Raible, C. C., Casado, M., & Yiou, P. (2015). A model-tested North Atlantic Oscillation reconstruction for the past millennium. *Nature*, 523(7558), 71–74. <https://doi.org/10.1038/nature14518>
- Piecuch, C. G., Calafat, F. M., Dangendorf, S., & Jordà, G. (2019). *The ability of barotropic models to simulate historical mean sea level changes from coastal tide gauge data. Surveys in Geophysics* (Vol. 40). Netherlands: Springer. <https://doi.org/10.1007/s10712-019-09537-9>
- Piecuch, C. G., Dangendorf, S., Gawarkiewicz, G. G., Little, C. M., Ponte, R. M., & Yang, J. (2019). How is New England coastal sea level related to the Atlantic meridional overturning circulation at 26° N? *Geophysical Research Letters*, 46, 5351–5360. <https://doi.org/10.1029/2019GL083073>
- Piecuch, C. G., Huybers, P., Hay, C. C., Kemp, A. C., Little, C. M., Mitrovica, J. X., et al. (2018). Origin of spatial variation in US East Coast sea-level trends during 1900–2017. *Nature*, 564(7736), 400–404. <https://doi.org/10.1038/s41586-018-0787-6>
- Rahmstorf, S., Box, J. E., Feulner, G., Mann, M. E., Robinson, A., Rutherford, S., & Schaffernicht, E. J. (2015). Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change*, 5, 1–6. <https://doi.org/10.1038/nclimate2554>
- Rasmussen, C. E., & Williams, C. K. I. (2006). *Gaussian Processes for Machine Learning*. Cambridge, MA: MIT Press. <http://www.gaussianprocess.org/gpml/>
- Ray, R. D., & Talke, S. A. (2019). Nineteenth-century tides in the Gulf of Maine and implications for secular trends. *Journal of Geophysical Research: Oceans*, 124, 7046–7067. <https://doi.org/10.1029/2019JC015277>
- Röthe, T. O., Bakke, J., Vasskog, K., Gjerde, M., D'Andrea, W. J., & Bradley, R. S. (2015). Arctic Holocene glacier fluctuations reconstructed from lake sediments at Mitrahavøya, Spitsbergen. *Quaternary Science Reviews*, 109, 111–125. <https://doi.org/10.1016/j.quascirev.2014.11.017>
- Saher, M. H., Gehrels, W. R., Barlow, N. L. M., Long, A. J., Haigh, I. D., & Blaauw, M. (2015). Sea-level changes in Iceland and the influence of the North Atlantic Oscillation during the last half millennium. *Quaternary Science Reviews*, 108, 23–36. <https://doi.org/10.1016/j.quascirev.2014.11.005>
- Sallenger, A. H., Doran, K. S., & Howd, P. A. (2012). Hotspot of accelerated sea-level rise on the Atlantic coast of North America. *Nature Climate Change*, 2(12), 884–888. <https://doi.org/10.1038/nclimate1597>
- Schmidt, G. A., Jungclauss, J. H., Ammann, C. M., Bard, E., Braconnot, P., Crowley, T. J., et al. (2012). Climate forcing reconstructions for use in PMIP simulations of the Last Millennium (v1.1). *Geoscientific Model Development*, 5(1), 185–191. <https://doi.org/10.5194/gmd-5-185-2012>
- Slangen, A. B. A., Church, J. A., Agosta, C., Fettweis, X., Marzeion, B., & Richter, K. (2016). Anthropogenic forcing dominates global mean sea-level rise since 1970. *Nature Climate Change*, 11–16. <https://doi.org/10.1038/nclimate2991>
- Thompson, P. R., Piecuch, C. G., Merrifield, M. A., McCreary, J. P., & Firing, E. (2016). Forcing of recent decadal variability in the Equatorial and North Indian Ocean. *Journal of Geophysical Research: Oceans*, 121, 6762–6778. <https://doi.org/10.1002/2016JC012132>
- Thornalley, D. J. R., Oppo, D. W., Ortega, P., Robson, J. I., Brierley, C. M., Davis, R., et al. (2018). Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150 years. *Nature*, 556(7700), 227–230. <https://doi.org/10.1038/s41586-018-0007-4>
- Trouet, V., Esper, J., Graham, N. E., Baker, A., Scourse, J. D., & Frank, D. C. (2009). Persistent positive North Atlantic oscillation mode dominated the Medieval Climate Anomaly. *Science (New York, N.Y.)*, 324(5923), 78–80. <https://doi.org/10.1126/science.1166349>
- Tsimplis, M. N., Shaw, A. G. P., Flather, R. A., & Woolf, D. K. (2006). The influence of the North Atlantic Oscillation on the sea-level around the northern European coasts reconsidered: The thermosteric effects. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, 364(1841), 845–856. <https://doi.org/10.1098/rsta.2006.1740>
- Vinther, B. M., Buchardt, S. L., Clausen, H. B., Dahl-Jensen, D., Johnsen, S. J., Fisher, D. A., et al. (2009). Holocene thinning of the Greenland ice sheet. *Nature*, 461(7262), 385–388. <https://doi.org/10.1038/nature08355>

- Willebrand, J., Philander, S. G. H., & Pacanowski, R. C. (1980). The oceanic response to large-scale atmospheric disturbances. *Journal of Physical Oceanography*. [https://doi.org/10.1175/1520-0485\(1980\)010<0411:tortls>2.0.co;2](https://doi.org/10.1175/1520-0485(1980)010<0411:tortls>2.0.co;2)
- Woodworth, P. L., Morales Maqueda, M. Á., Roussenov, V. M., Williams, R. G., & Hughes, C. W. (2014). Mean sea-level variability along the northeast American Atlantic coast and the roles of the wind and the overturning circulation. *Journal of Geophysical Research: Oceans*, 119, 8916–8935. <https://doi.org/10.1002/2014JC010520>
- Woodworth, P. L., Morales Maqueda, M. Á., Gehrels, W. R., Roussenov, V. M., Williams, R. G., & Hughes, C. W. (2017). Variations in the difference between mean sea level measured either side of Cape Hatteras and their relation to the North Atlantic Oscillation. *Climate Dynamics*, 49(7–8), 1–19. <https://doi.org/10.1007/s00382-016-3464-1>
- Woolf, D. K., Shaw, A. G. P., & Tsimplis, M. N. (2003). The influence of the North Atlantic Oscillation on sea-level variability in the North Atlantic region. *Journal of Atmospheric & Oceanic Technology*, 20(4), 145–167. <https://doi.org/10.1029/2002JO001633>
- Yan, Z., Tsimplis, M. N., & Woolf, D. (2004). Analysis of the relationship between the North Atlantic oscillation and sea-level changes in northwest Europe. *International Journal of Climatology*, 24(6), 743–758. <https://doi.org/10.1002/joc.1035>
- Yin, J., & Goddard, P. B. (2013). Oceanic control of sea level rise patterns along the East Coast of the United States. *Geophysical Research Letters*, 40, 5514–5520. <https://doi.org/10.1002/2013GL057992>
- Yin, J., Schlesinger, M. E., & Stouffer, R. J. (2009). Model projections of rapid sea-level rise on the northeast coast of the United States. *Nature Geoscience*, 2(4), 262–266. <https://doi.org/10.1038/ngeo462>

## References From the Supporting Information

- Barlow, N. L. M., Shennan, I., Long, A. J., Gehrels, W. R., Saher, M. H., Woodroffe, S. A., & Hillier, C. (2013). Salt marshes as late Holocene tide gauges. *Global and Planetary Change*, 106, 90–110. <https://doi.org/10.1016/j.gloplacha.2013.03.003>
- Birks, H. J. B. (1995). Quantitative palaeoenvironmental reconstructions. In D. Maddy & J. S. Brew (Eds.), *Statistical Modelling of Quaternary Science Data* (pp. 161–254). Cambridge: Quaternary Research Association.
- Blaauw, M., & Christen, J. A. (2011). Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis*, 6(3), 457–474. <https://doi.org/10.1214/11-BA618>
- Brain, M. J., Long, A. J., Woodroffe, S. A., Petley, D. N., Milledge, D. G., & Parnell, A. C. (2012). Modelling the effects of sediment compaction on salt marsh reconstructions of recent sea-level rise. *Earth and Planetary Science Letters*, 345–348, 180–193. <https://doi.org/10.1016/j.epsl.2012.06.045>
- Bricker-Urso, S., Nixon, S. W., Cochran, J. K., Hirschberg, D. J., & Hunt, C. (1989). Accretion rates and sediment accumulation in Rhode-Island salt marshes. *Estuaries*, 12(4), 300–317.
- Carter, R. W. G., Orford, J. D., Jennings, S. C., Shaw, J., & Smith, J. P. (1992). Recent evolution of a paraglacial estuary under conditions of rapid sea-level rise: Chezzetcook Inlet, Nova Scotia. *Proceedings of the Geologists' Association*, 103, 167–185. [https://doi.org/10.1016/S0016-7878\(08\)80228-3](https://doi.org/10.1016/S0016-7878(08)80228-3)
- Edwards, R. J., Van de Plassche, O., Gehrels, W. R., & Wright, A. J. (2004). Assessing sea-level data from Connecticut, USA, using a foraminiferal transfer function for tide level. *Marine Micropaleontology*, 51(3–4), 239–255. <https://doi.org/10.1016/j.marmicro.2003.11.003>
- Gehrels, W. R., & Belknap, D. F. (1993). Neotectonic history of eastern Maine evaluated from historic sea-level data and 14C dates on salt-marsh peats. *Geology*, 21(7), 615–618. [https://doi.org/10.1130/0091-7613\(1993\)021<0615:NHOEME>2.3.CO;2](https://doi.org/10.1130/0091-7613(1993)021<0615:NHOEME>2.3.CO;2)
- Gehrels, W. R., Belknap, D. F., & Kelley, J. T. (1996). Integrated high precision analyses of Holocene relative sea-level changes: Lessons from the coast of Maine. *Geological Society of America Bulletin*, 108(9), 1073–1088. [https://doi.org/10.1130/0016-7606\(1996\)108<1073:IHPAOH>2.3.CO;2](https://doi.org/10.1130/0016-7606(1996)108<1073:IHPAOH>2.3.CO;2)
- Gehrels, W. R., Roe, H. M., & Charman, D. J. (2001). Foraminifera, testate amoebae and diatoms as sea-level indicators in UK salt marshes: A quantitative multiproxy approach. *Journal of Quaternary Science*, 16(3), 201–220. <https://doi.org/10.1002/jqs.588>
- Gehrels, W. R., Milne, G. A., Kirby, J. R., Patterson, R. T., & Belknap, D. F. (2004). Late Holocene sea-level changes and isostatic crustal movements in Atlantic Canada. *Quaternary International*, 120(1), 79–89. <https://doi.org/10.1016/j.quaint.2004.01.008>
- Goodman, J. E., Wood, M. E., & Gehrels, W. R. (2007). A 17-yr record of sediment accretion in the salt marshes of Maine (USA). *Marine Geology*, 242(1–3), 109–121. <https://doi.org/10.1016/j.margeo.2006.09.017>
- Graney, J. R., Halliday, A. N., Keeler, G. J., Nriagu, J. O., Robbins, J. A., & Norton, S. A. (1995). Isotopic record of lead pollution in lake sediments from the northeastern United States. *Geochimica et Cosmochimica Acta*, 59(9), 1715–1728. [https://doi.org/10.1016/0016-7037\(95\)00077-D](https://doi.org/10.1016/0016-7037(95)00077-D)
- Jennings, S. C., Carter, R. W. G., & Orford, J. D. (1993). Late Holocene salt marsh development under a regime of rapid relative-sea-level rise: Chezzetcook Inlet, Nova Scotia. Implications for the interpretation of palaeomorph sequences. *Canadian Journal of Earth Sciences*, 30(7), 1374–1384. <https://doi.org/10.1139/e93-118>
- Jennings, S. C., Carter, R. W. G., & Orford, J. D. (1995). Implications for sea-level research of salt marsh and mudflat accretionary processes along paraglacial barrier coasts. *Marine Geology*, 124(1–4), 129–136. [https://doi.org/10.1016/0025-3227\(95\)00036-X](https://doi.org/10.1016/0025-3227(95)00036-X)
- Juggins, S. (2003). C2: A Microsoft Windows Program for Developing and Applying Palaeoecological Transfer Functions and for Visualising Multi-Proxied Stratigraphic Datasets. Newcastle upon Tyne: University of Newcastle.
- Kylander, M. E., Weiss, D. J., & Kober, B. (2009). Two high resolution terrestrial records of atmospheric Pb deposition from New Brunswick, Canada, and Loch Laxford, Scotland. *Science of the Total Environment*, 407(5), 1644–1657. <https://doi.org/10.1016/j.scitotenv.2008.10.036>
- Kemp, A. C., Sommerfield, C. K., Vane, C. H., Horton, B. P., Chenery, S., Anisfeld, S., & Nikitina, D. (2012). Use of lead isotopes for developing chronologies in recent salt-marsh sediments. *Quaternary Geochronology*, 12, 40–49. <https://doi.org/10.1016/j.quageo.2012.05.004>
- Marshall, W. A., Gehrels, W. R., Garnett, M. H., Freeman, S. P. H. T., Maden, C., & Xu, S. (2007). The use of “bomb spike” calibration and high-precision AMS14C analyses to date salt-marsh sediments deposited during the past three centuries. *Quaternary Research*, 68(3). <https://doi.org/10.1016/j.yqres.2007.07.005>
- Orford, J. D., Carter, R. W. G., & Forbes, D. L. (1991). Gravel barrier migration and sea level rise: Some observations from Story Head, Nova Scotia, Canada. *Journal of Coastal Research*, 7(2), 477–489. <https://doi.org/10.2307/4297854>
- Orford, J. D., Carter, R. W. G., & Jennings, S. C. (1996). Control domains and morphological phases in gravel-dominated coastal barriers of Nova Scotia. *Journal of Coastal Research*, 12(3), 589–604. <https://doi.org/10.2307/4298507>
- Scott, D. B. (1977). Distribution and Population Dynamics of Marsh-Estuarine Foraminifera with Applications to Relocating Holocene Sea Levels. PhD thesis, Dalhousie University, Halifax, Nova Scotia, Canada.



- Scott, D. B., & Medioli, F. S. (1980). Quantitative studies of marsh foraminiferal distributions in Nova Scotia: Implications for sea level studies. In *Cushman Foundation for Foraminiferal Research Special Publication* 17 (pp. 1–57).
- Scott, D. B., Boyd, R., & Medioli, F. S. (1987). Relative sea-level changes in Atlantic Canada: Observed level and sedimentological changes vs. theoretical models. In D. Nummedal, O. H. Pilkey Jr., & J. D. Howard (Eds.), *Sea Level Fluctuation and Coastal Evolution. Society of Economic Paleontologists and Mineralogists Special Publication* 41 (pp. 87–96).
- Scott, D. B., Gayes, P. T., & Collins, E. S. (1995). Mid-Holocene precedent for a future rise in sea-level along the Atlantic Coast of North America. *Journal of Coastal Research*, 11(3), 615–622. <https://doi.org/4298366>
- Watcham, E. P., Shennan, I., & Barlow, N. L. M. (2013). Scale considerations in using diatoms as indicators of sea-level change: Lessons from Alaska. *Journal of Quaternary Science*, 28(2), 165–179. <https://doi.org/10.1002/jqs.2592>
- Wood, M. E., Kelley, J. T., & Belknap, D. F. (1989). Patterns of sediment accumulation in the tidal marshes of Maine. *Estuaries*, 12(4), 237–246.